Understanding the r-process

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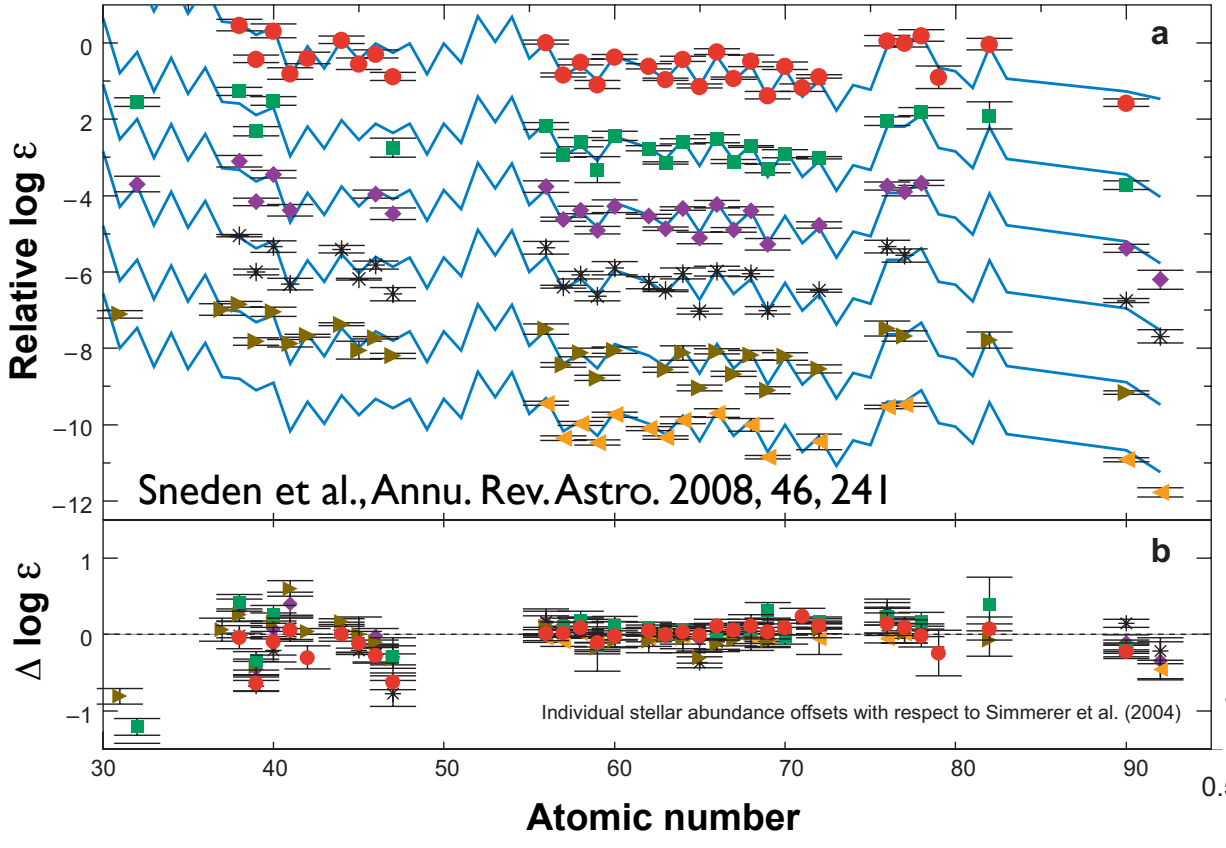
- r-process
- Nuclear physics
- CARIBU (Masses, half-lives and β-delayed neutron branching ratios)

Open questions:

- Where does the r-process occur?
- What are the actual reaction sequences?
- Are there multiple processes in the early Galaxy?
- What can the r-process tell us about physics of extreme environments?

Metal-poor stars



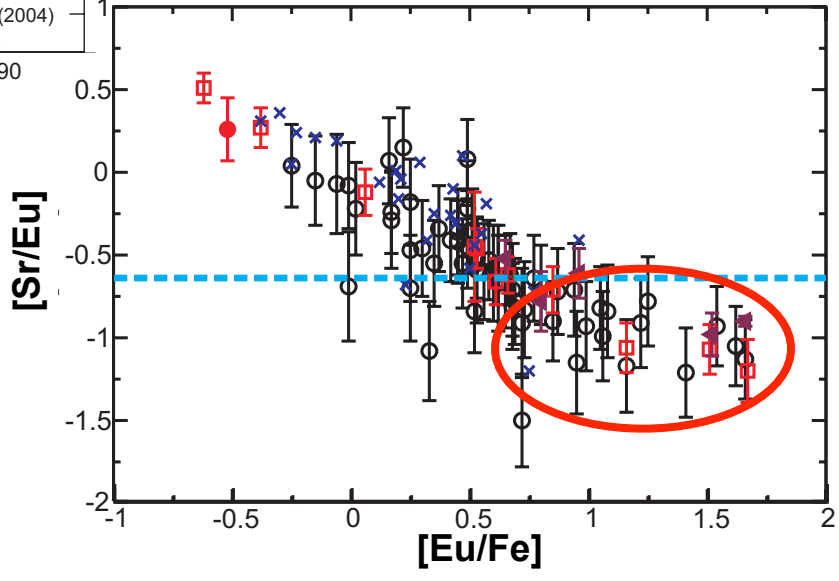
Eu: r-process element

[Fe/H] < -2.5

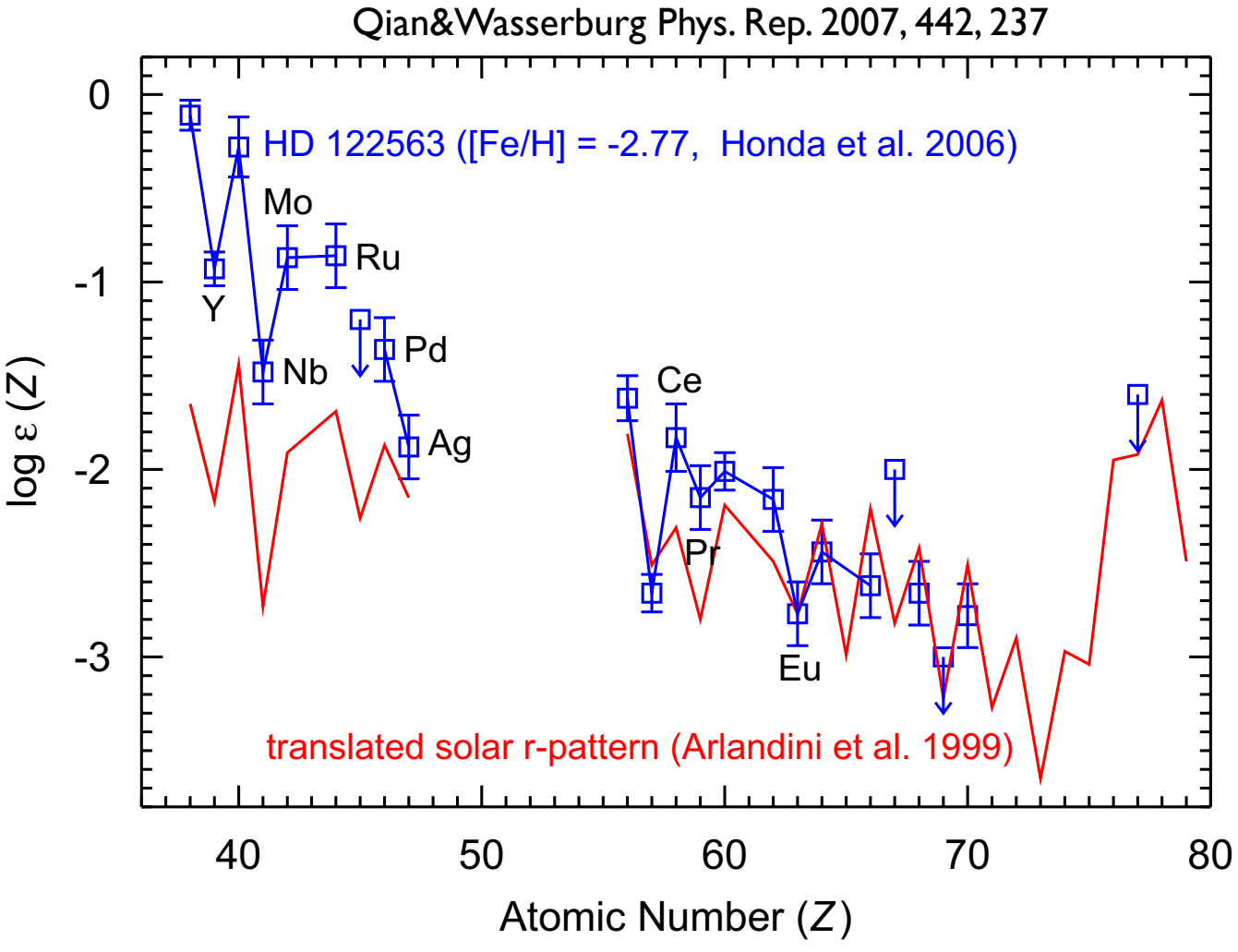
Metal poor (old stars)

- CS 22892-052: Sneden et al. (2003)
- HD 115444: Westin et al. (2000)
- BD+17°324817: Cowan et al. (2002)
- CS 31082-001: Hill et al. (2002)
- HD 221170: Ivans et al. (2006)
- HE 1523-0901: Frebel et al. (2007)

Montes et al. ApJ 2007, 671, 1685



Multiple r-processes?



r-process:
Most of the elements heavier than Sr

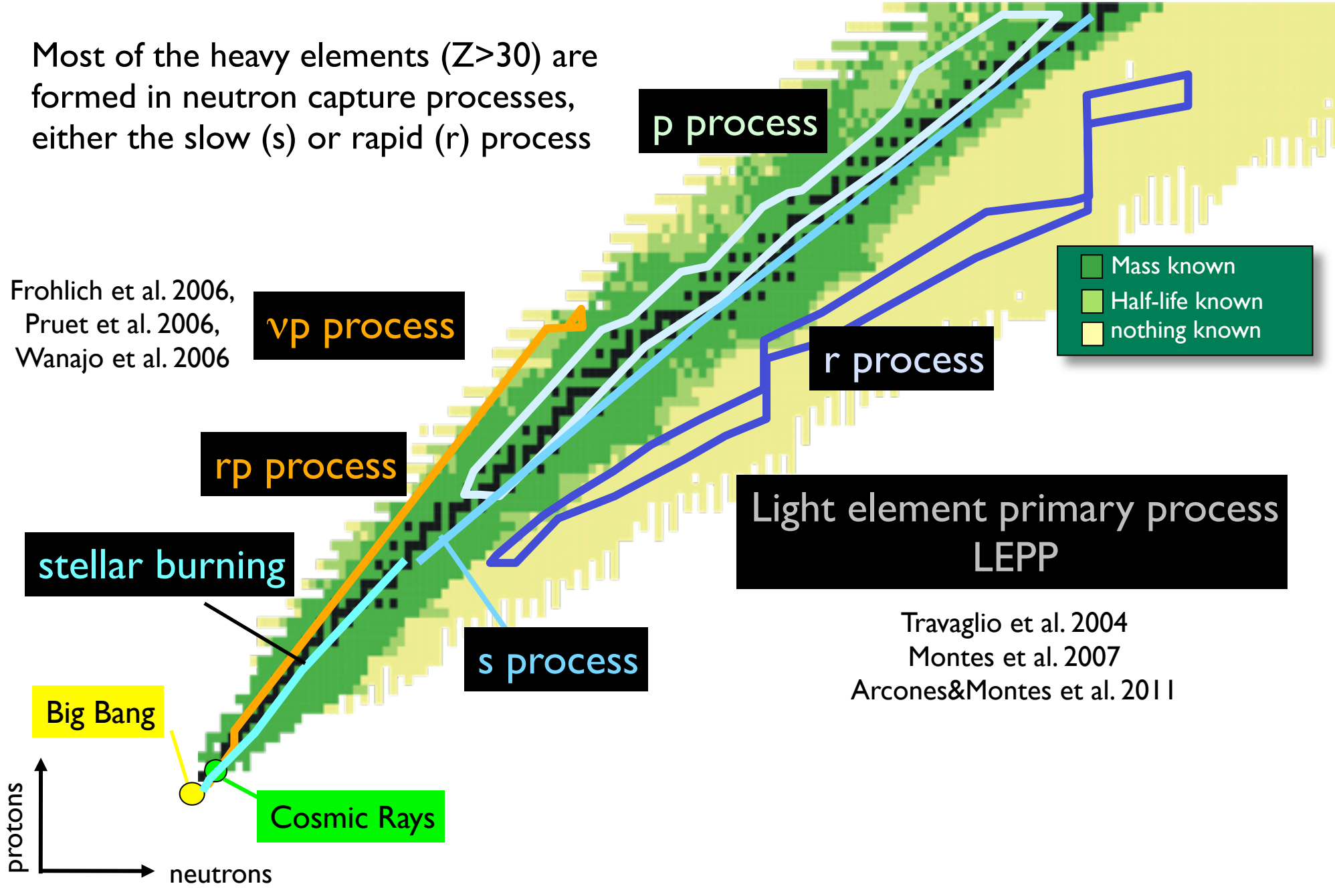
LEPP:
Only Sr - Ag?

Light Element Primary Process
LEPP

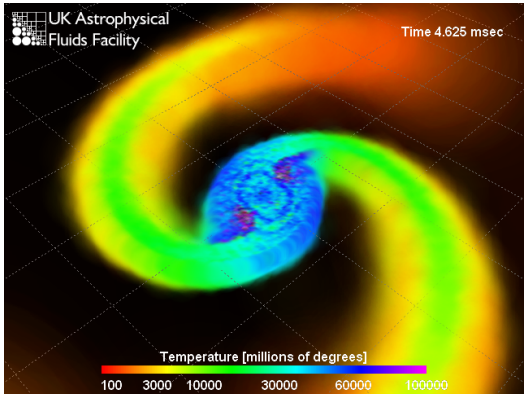
- Weak r-process (Truran&Cowan 2000)
- Charge-particle reaction process (Woosley&Hoffman 1992; Freiburghaus et al. 1999)

Nucleosynthesis processes

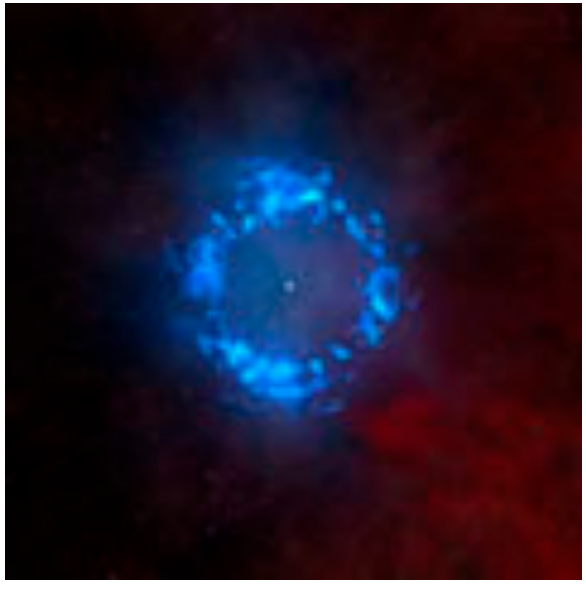
Most of the heavy elements (Z>30) are formed in neutron capture processes, either the slow (s) or rapid (r) process

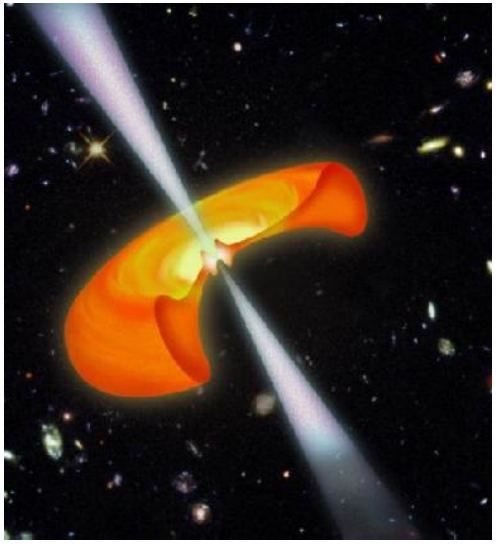


Where does the r-process occur?



Neutron star mergers (Freiburghaus et al. 1999, Goriely et al. 2005)
Mergers rate too low to explain [Eu/Fe] ratio
Composition of ejected material unknown

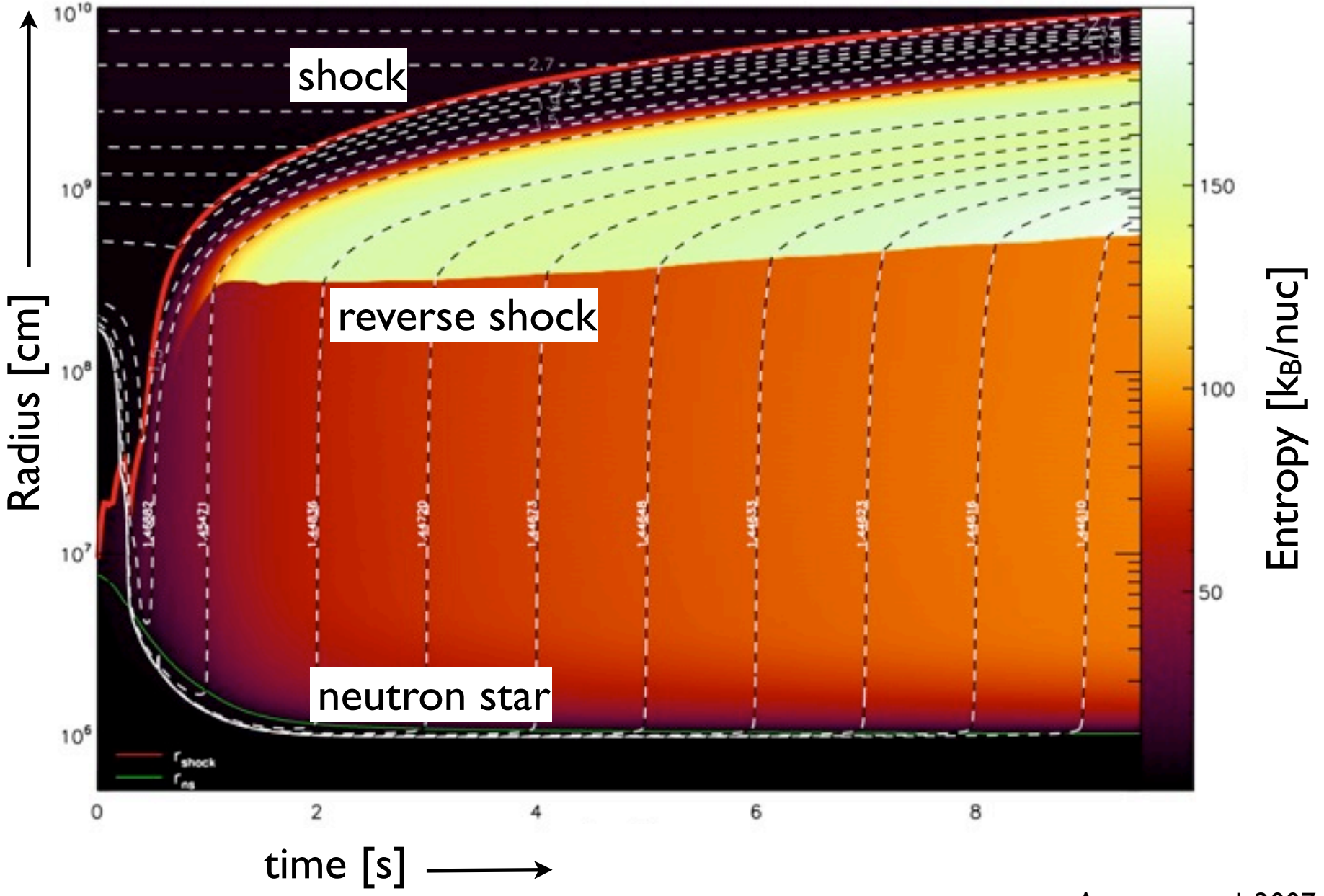




Gamma ray bursts
(Surman et al. 2005)

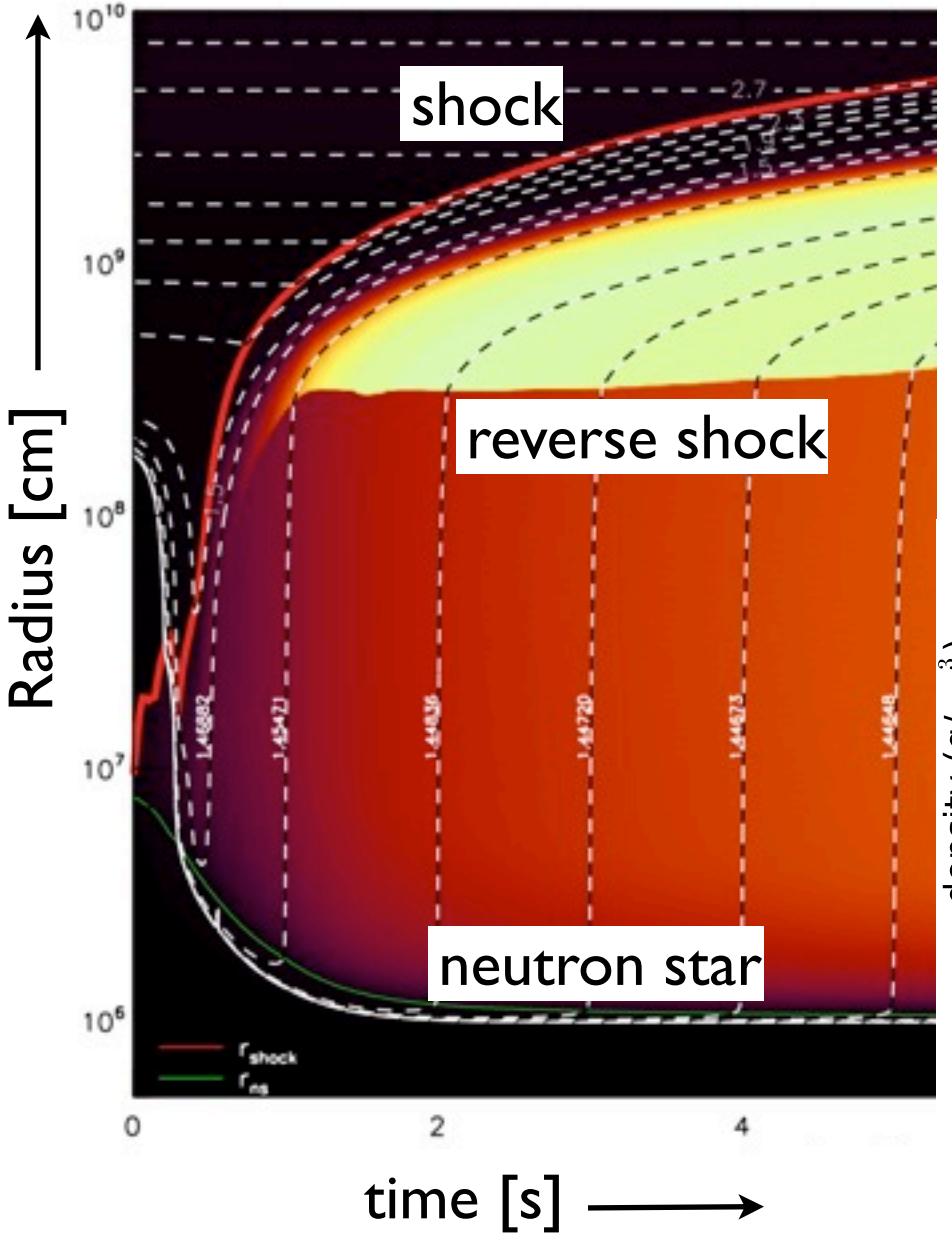
Supernovae
ONeMg core collapse (Wanajo et al. 2003) Y(n) not high enough
Jets in core-collapse supernovae (Cameron 2001)
ν-driven wind (Woosley et al. 1992, Terasava et al. 2001) entropy not high enough
Neutrino-induced in He-shells (Epstein et al. 1988, Banerjee et al. 2011)

ν-driven wind scenario

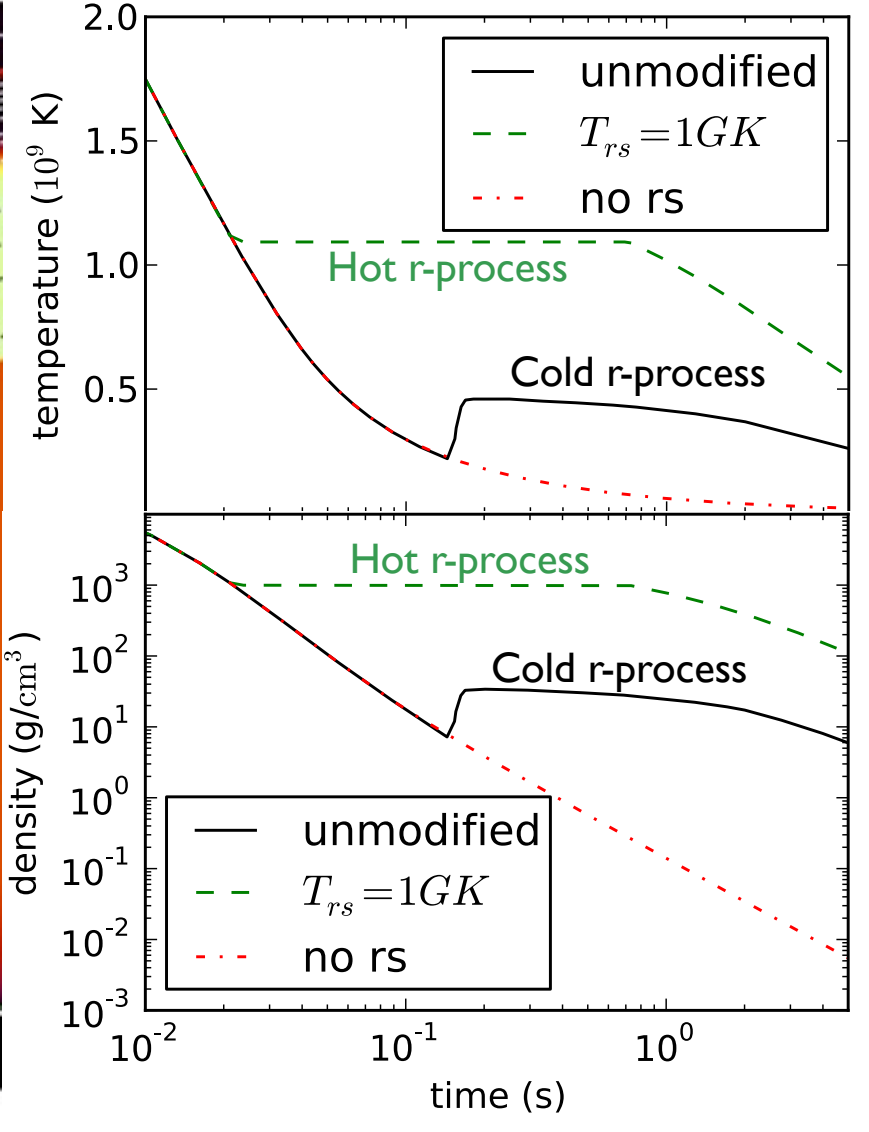


Arcones et al. 2007

ν-driven wind simulation

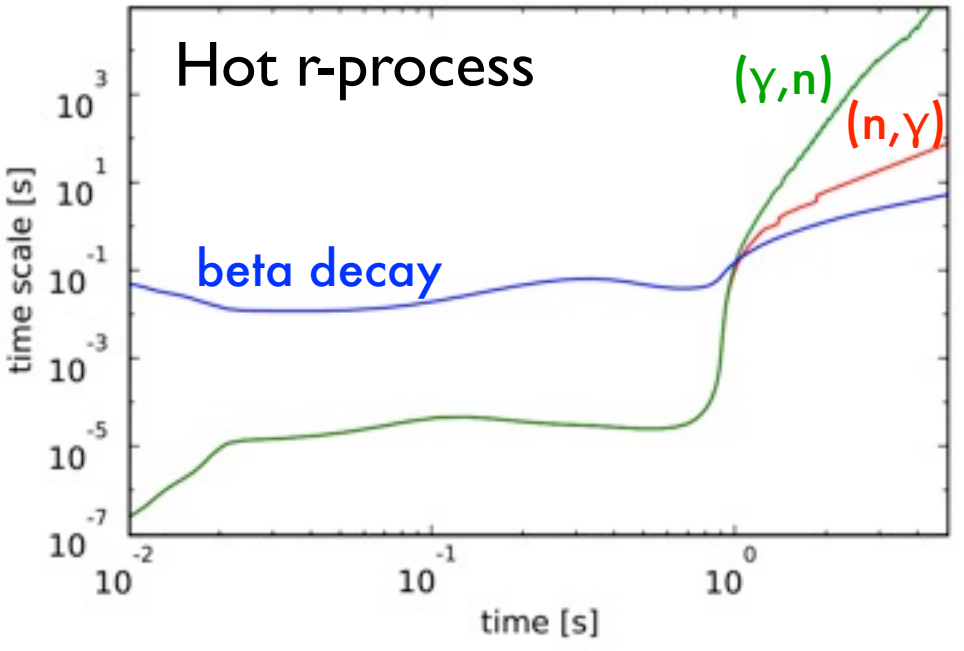


Arcones & Martinez-Pinedo 2011



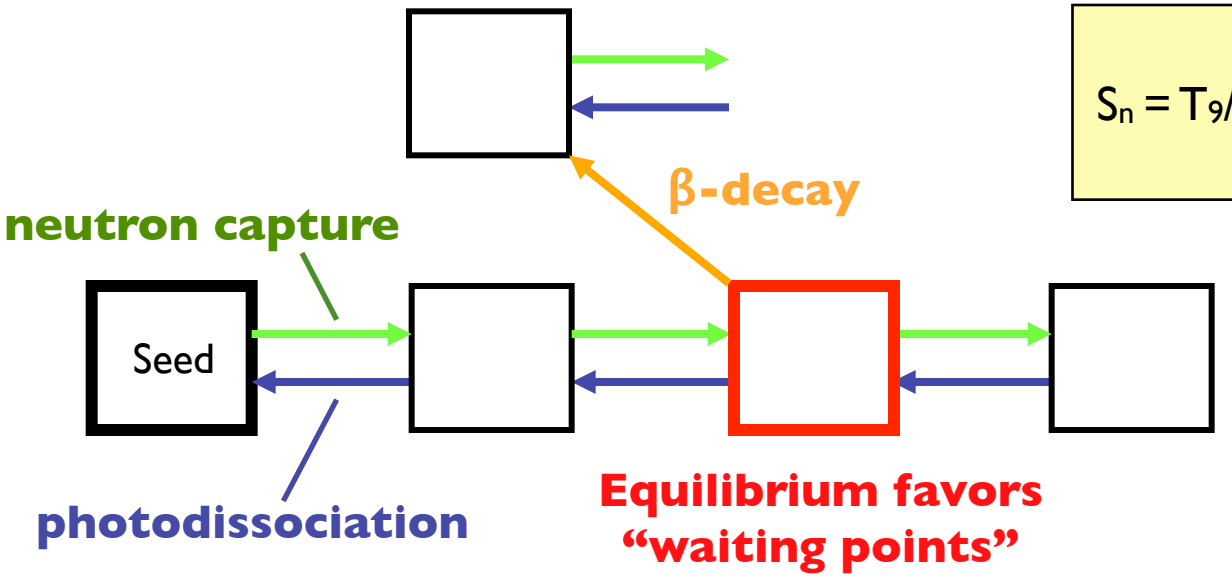
Hot r-process

Arcones & Martinez-Pinedo 2011



Need:

- Masses (traps)
- Half-lives (Si detector stacks, combine with γ-spectroscopy)
- Neutron capture rates after neutron freeze-out
- Neutron emission probabilities (neutron detector)
- Maybe fission and neutrino interaction rates



Location of path

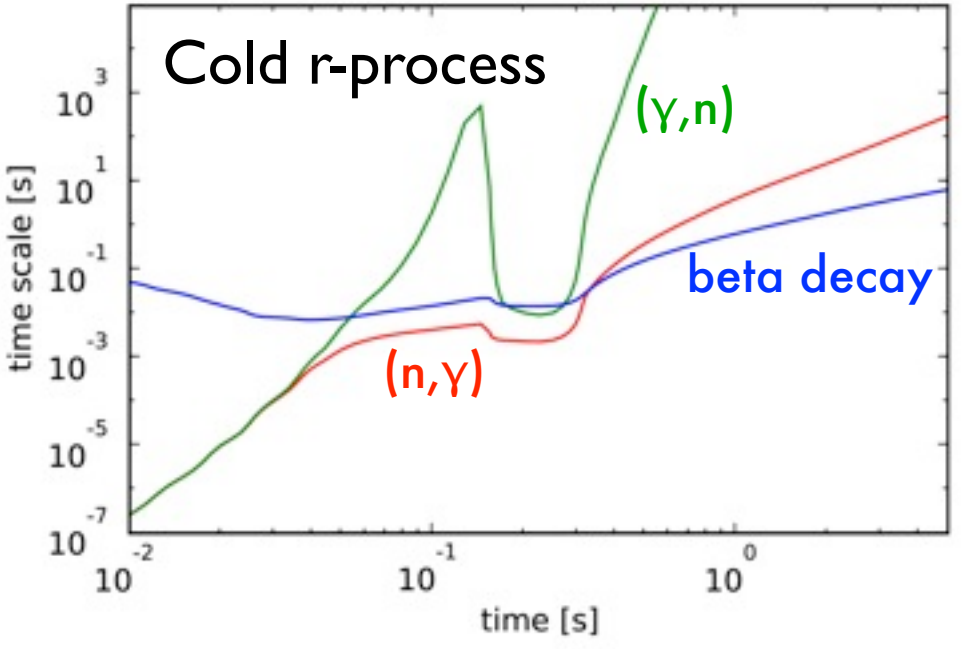
$S_n = T_9/5.04 \times (34.08 + 1.5 \log T_9 - 1.5 \log n_n)$

= 2.5-4 MeV

The evolution takes place under (n,γ)-(γ,n) equilibrium (classical r-process, Seeger, Fowler and Clayton1965, Kratz et al. 1993)

Cold r-process

Arcones & Martinez-Pinedo 2011



Location of path
S_n = 2-4 MeV

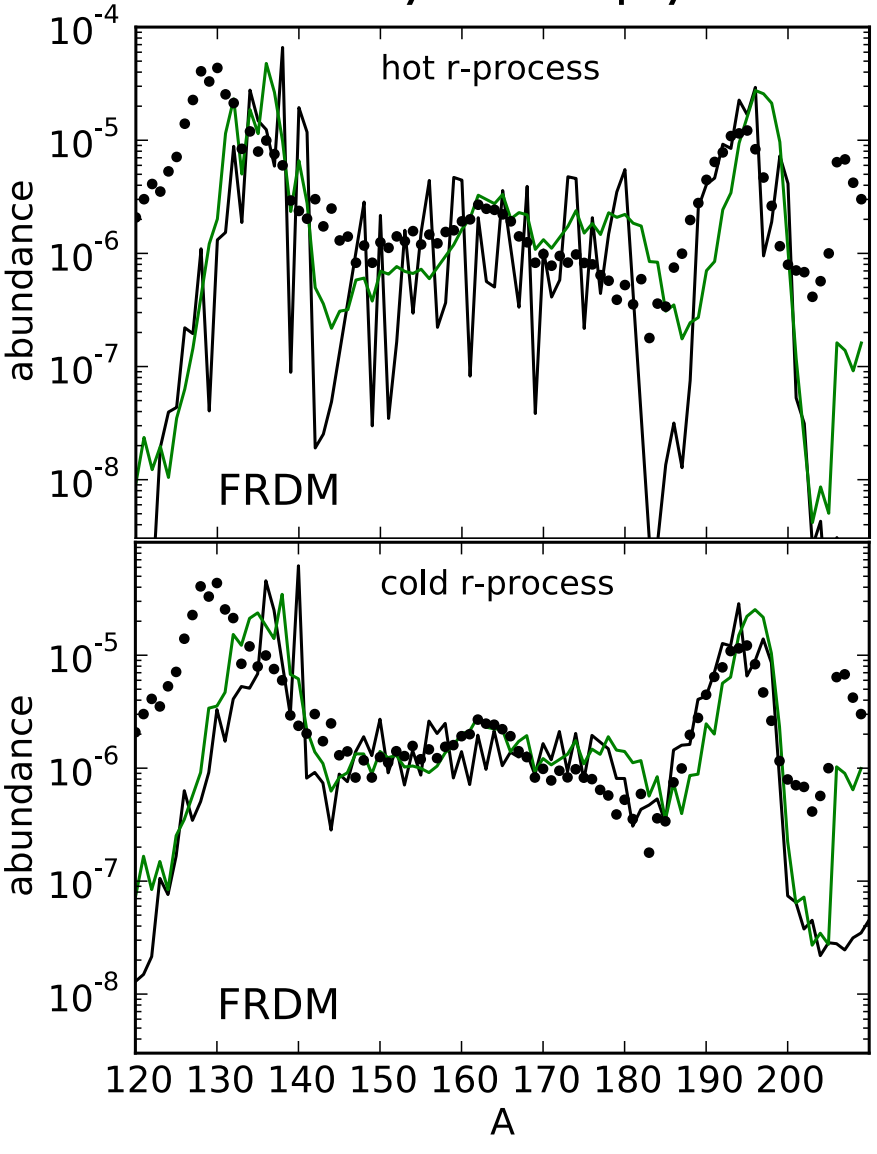
Competition between beta decay and neutron capture (Blake & Schramm 1976, Wanajo 2007, Janka & Panov 2009)

Need:

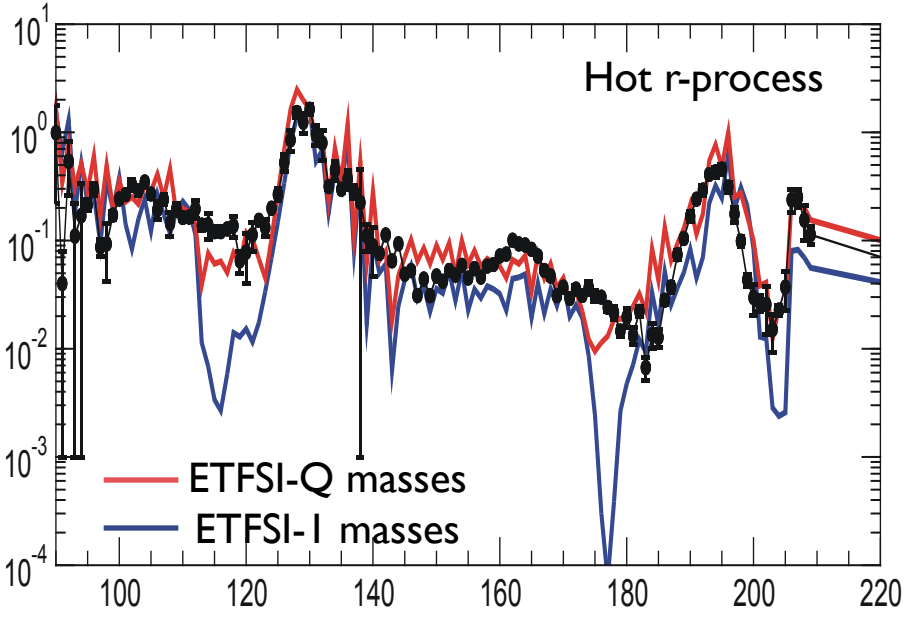
- Neutron capture rates (masses)
- Half-lives
- Neutron emission probabilities
- Maybe fission and neutrino interaction rates

Sensitivity of r-process to astro and nuclear physics

Sensitivity to astrophysics



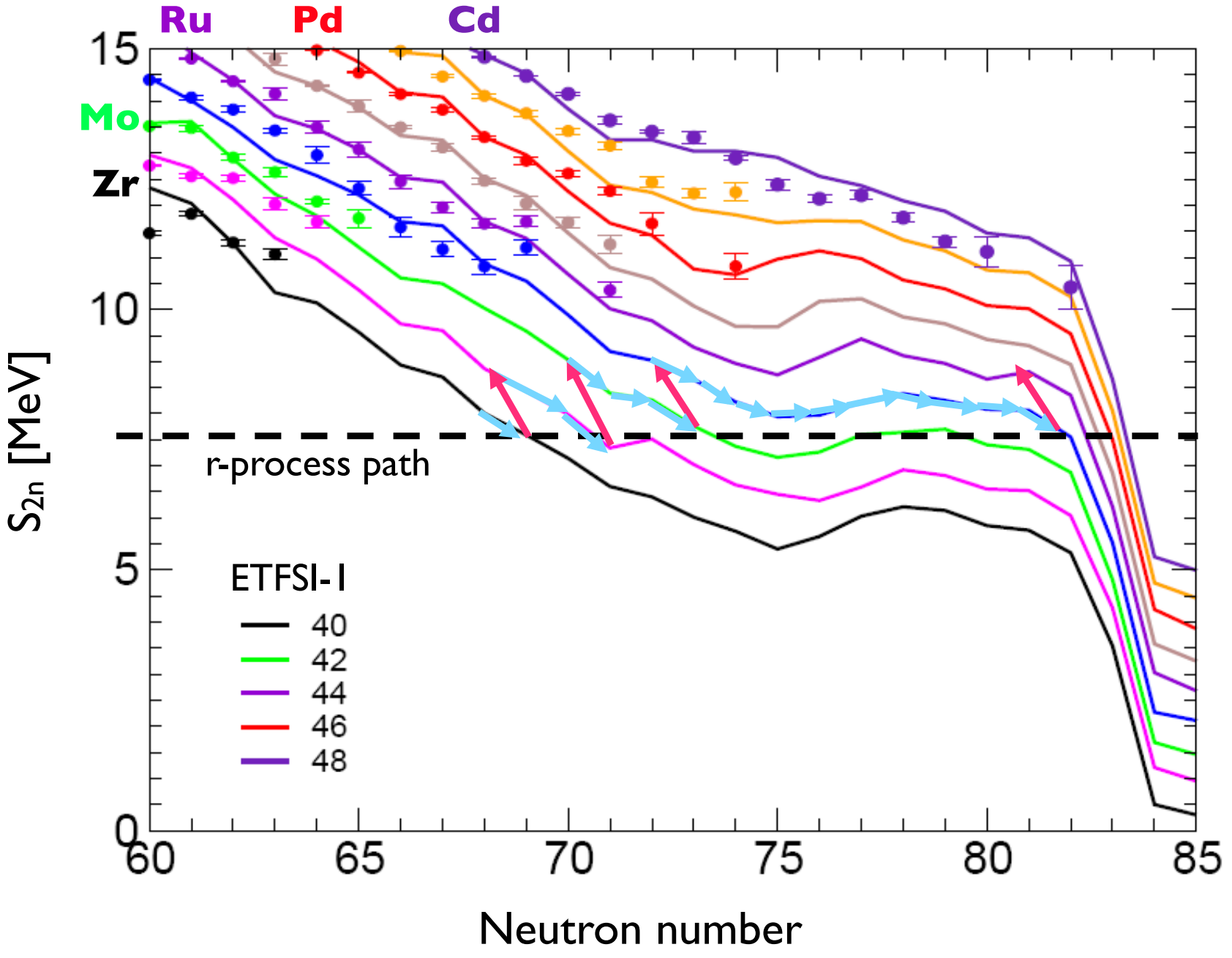
Sensitivity to nuclear physics



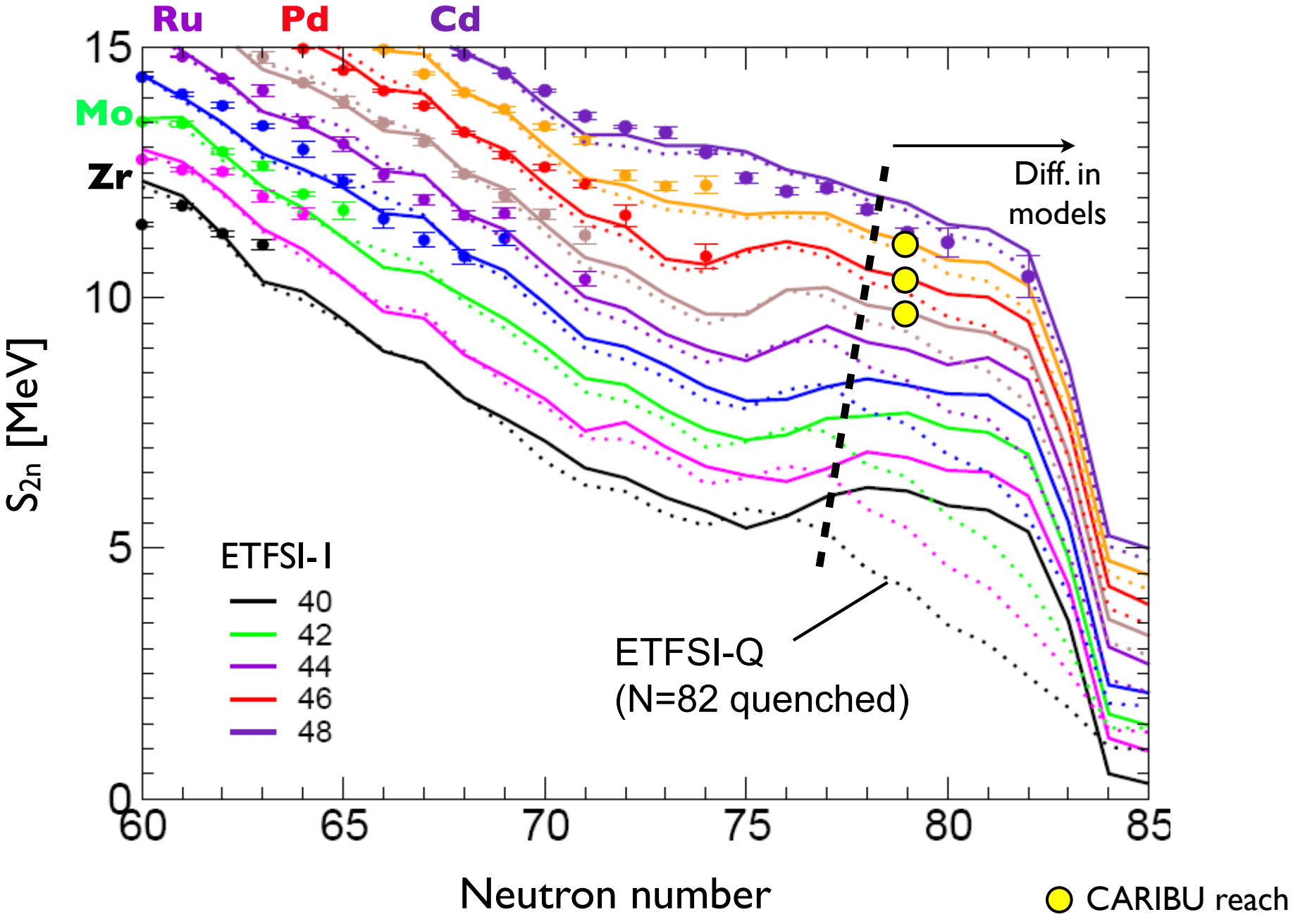
Comparison to observations:

- Obtain neutron density, temperature, time
- Neutrino interactions
- Determines which model is correct
- Convoluted with nuclear physics

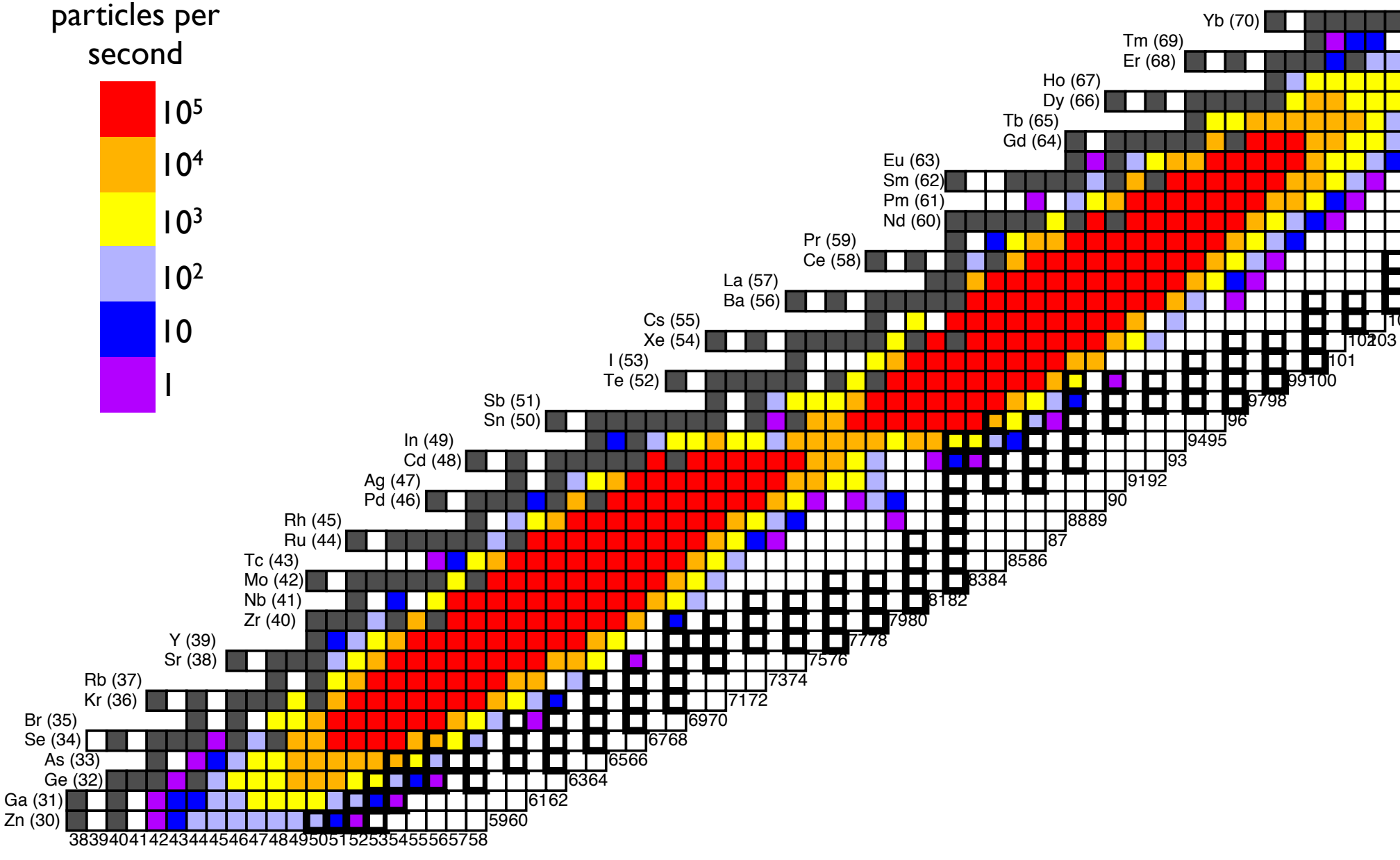
Shell quenching effect on masses/r-process



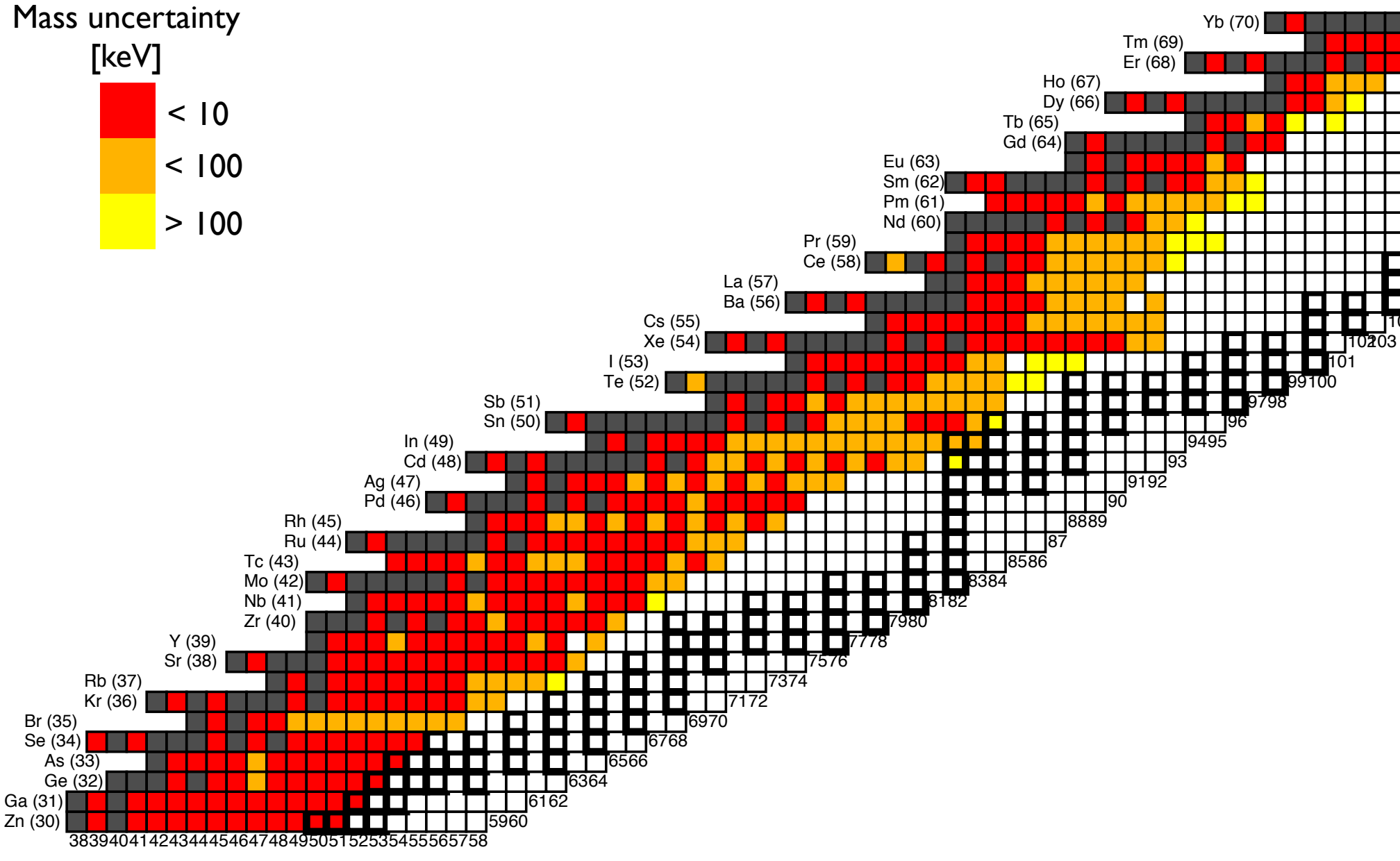
Shell quenching effect on masses/r-process



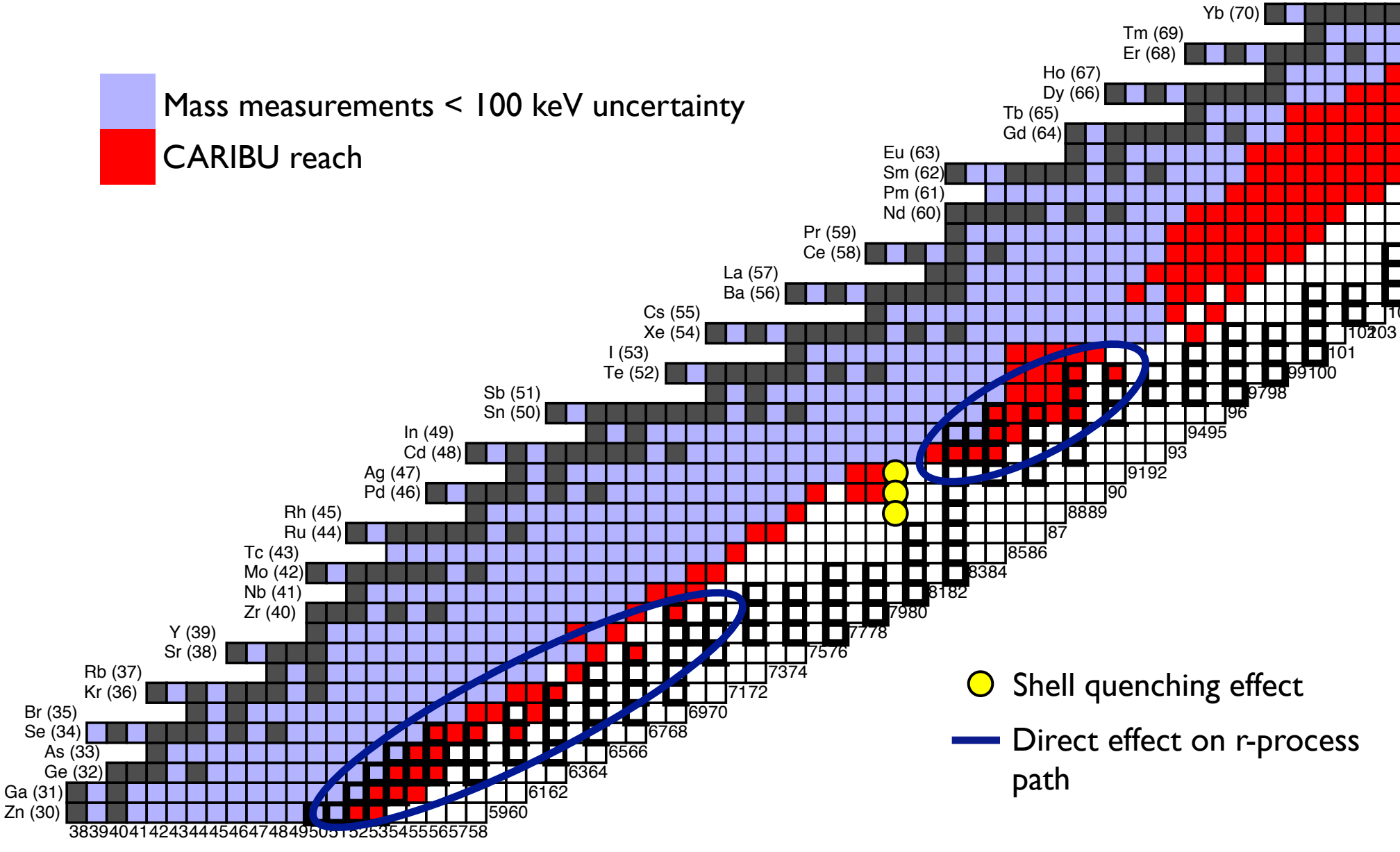
CARIBU beam intensities



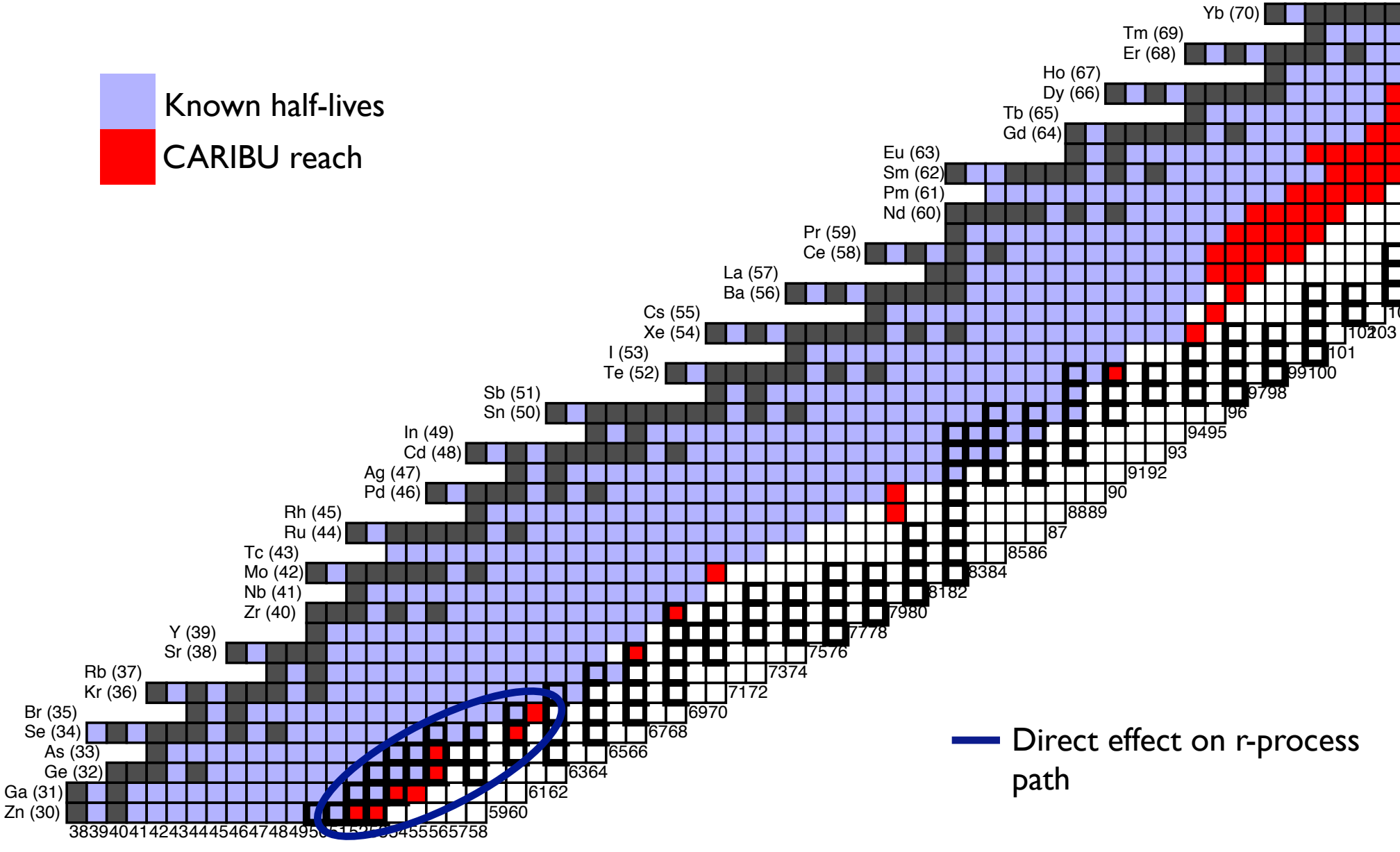
Mass measurements status



Possible CARIBU mass measurements

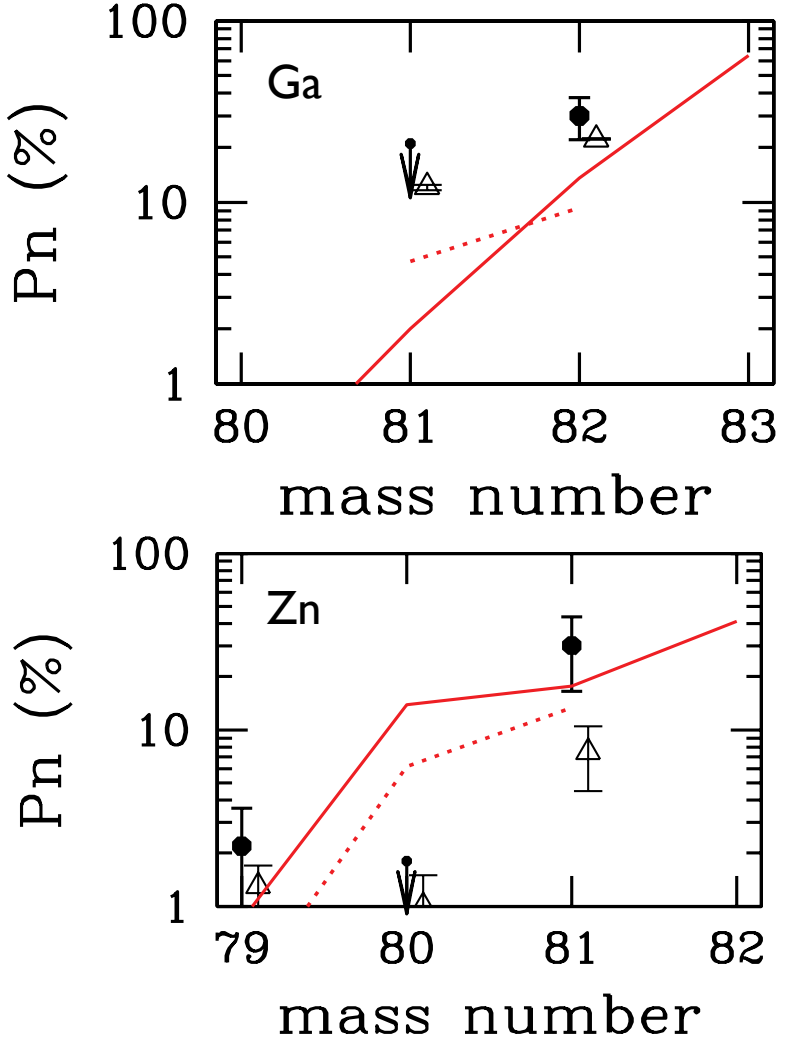


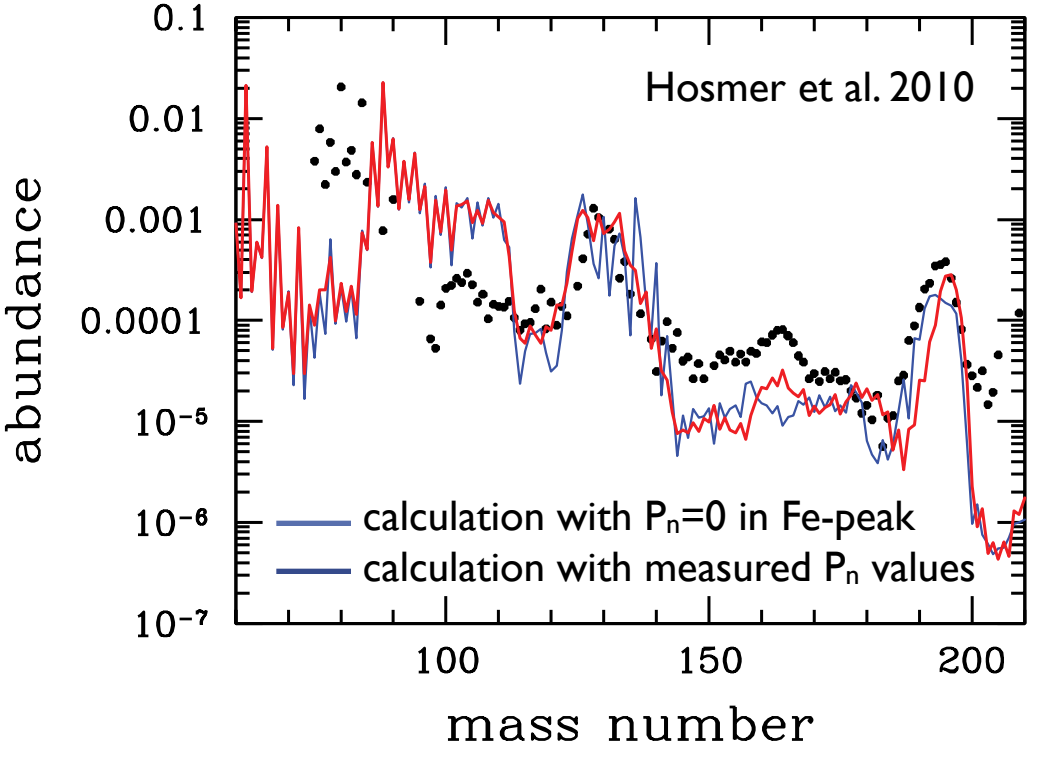
Possible CARIBU half-life measurements



β-decay spectroscopy

β-delayed neutron branching ratios





Possible P_n measurements:

- Extend to $^{82\text{-}83}$Zn, $^{85\text{-}86}$Ga, ^{88}Ge, ^{89}Ge, ^{89}As, ^{94}Se and ^{96}Br
- Progenitor of Sr, Y, Zr abundances (disentangle main r-process and LEPP)
- Nuclear physics in solid basis in the A=80-95 region

Summary

- New observations will require similar advances in nuclear physics to address the many compelling scientific questions of the r-process
- Neutron-rich nuclei far from stability are important in the r-process
- CARIBU rates will enable the study of nuclei relevant for r-process nucleosynthesis

- Mass measurements (δ<10-100 keV) will have a direct effect on r-process calculations and will address the question about shell-quenching at the N=82 shell closure
- Half-lives and P_n measurements will put the nuclear physics in the r-process responsible for Sr, Y and Zr abundances in a solid basis

Thanks to Hendrik Schatz for material